Deep Nulling of Visible Laser Light with a Rotational Shearing Interferometer

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Nulling interferometry[1-4], a proposed technique for ``dimming" a star relative to its surroundings, has the potential to enable direct imaging of planets orbiting nearby stars. The technique consists of combining starlight from two telescopes out of phase, but to date it remains largely a theoretical construct, due to the extreme levels of pathlength, intensity, polarization, and wavefront control necessary to achieve useful levels of starlight nulling. Initial astronomical observations exploiting destructive interference[4] have demonstrated starlight rejection to a part in 25, but much deeper rejection is required for planetary searches. Here we present initial results from a series of laboratory experiments aimed at demonstrating the feasibility of deep nulling. As a first step, we report the successful nulling of light from a red laser diode to one part in 25,000 with a rotational shearing interferometer. Further experimental steps on the road to planetary imaging, including the extension of these nulling techniques to broadband light and into the infrared, as well as a demonstration of the long-term maintenance of deep nulls, are now also within reach.

What laboratory nulling ratio (N = [rejection]$^{-1}$) would verify the potential of nulling interferometry to an adequate level? To reduce the incident flux from a solar-type star to the level of a possible terrestrial companion, a stellar nulling ratio of about 10^{-9} would be required at visible wavelengths[5]. However, in the thermal infrared (10 μm) region, where NASA's proposed Terrestrial Planet Finder (TPF) mission[6] is slated to operate, a much more modest nulling ratio of 10^{-6} would suffice[5]. In the absence of other limitations, the null depth for monochromatic radiation of wavelength λ is given in terms of the phase error, ϕ (or the optical path difference x_{OPD}) between two combining beams by

$$N = (\phi/2)^2 = (\pi x_{OPD}/\lambda)^2. \quad (1)$$

Thus to maintain a net null depth of 10^{-6} at λ= 10 μm in the presence of other disturbances, an OPD accuracy of about 1 nm, or $\lambda/10^4$, is required. Such a degree of pathlength control is roughly an order of magnitude more precise than current state of the art capabilities in both laboratory and astronomical interferometers. In addition to this formidable challenge, there are others: the two combining beams must have intensities matched to 0.1%, polarization vectors antiparallel to better than 0.1°, and a degree of wavefront quality which is only attainable upon passage through a single-mode spatial filter[2]. Thus, substantial challenges lie ahead.

As a first step to demonstrating that an undertaking as ambitious as TPF is viable, NASA plans a demonstration of nulling with the requisite nanometer accuracy on its precursor Space Interferometer Mission (SIM)[7]. As however SIM is to operate at optical wavelengths, the necessary operating characteristics require translation. Thus, for e.g. red light (λ=600 nm), the λ^2 dependence of the null depth (Eq. 1) implies that the target OPD accuracy of 1 nm (λ/600 now) corresponds to an optical null depth of order 10^{-4}. Achieving such a performance would thus not only verify OPD control at the required level, but also test all of the basic aspects of the optical prescription for nulling, including field flipping, power matching, and wavefront cleanup. A null of 10^{-4} at visible wavelengths is thus an appropriate goal for initial laboratory experiments.

For deep cancellation of the broadband starlight received by two separate telescope apertures, it is necessary to combine the two beams so that a completely achromatic field reversal occurs at zero OPD between the combining beams. A clever way to achieve this is with a geometric flip of the electric field vector, such as is provided by a rotational shearing interferometer[2,8-10]. Several applicable variants have been proposed[9,10], but the simplest, involving only flat mirrors, is based on a pair of orthogonal rooftop mirrors (Fig.1a). In such a system, each rooftop mirror flips only that polarization component which is normal to its joint line, and the net result of reflection from a pair of orthogonal rooftops is a relative flip of the electric field vector. The inclusion of two additional flat 45° mirrors just prior to the two rooftops, as in Fig. 1, makes the net reflection geometries identical in the two arms[9] (in each arm, each polarization component experiences 2 s-plane and 2 p-plane reflections at the same 45° incidence angle). Thus, for reasons of maximum symmetry, as well as earlier encouraging results with this approach[11], an ``orthogonal rooftop" rotational shearing interferometer was selected for our experiments. A photograph of our laboratory nulling interferometer is shown in Fig. 1b. In Fig. 2 it can be seen that the colors of white light fringes in the pupil plane are indeed symmetric about a central dark fringe, confirming the achromatic nature of the destructive interference induced by the relative field flip.

It is of course desirable to simulate as closely as possible the ultimate goal of a pair of imperfect telescope apertures intercepting perfectly collimated starlight. To ensure that the collimated input beam adequately mimics a starlight beam, we used a 635 nm laser diode coupled to the nulling optics through a single-mode fiber. The essentially perfect single-mode beam diverging from the fiber tip is then collimated to a 25 mm diameter beam by an achromatic doublet. From this point onward, optics of typical quality (λ/10) were employed, so that after propagation of the collimated input beam through the optics, a fairly typically aberrated wavefront results. As a result of these aberrations, different parts of the aprerture would be nulled at different overall OPD settings, thus requiring wavefront cleanup by a single mode spatial filter[2] to achieve a global deep null. (Otherwise wavefront aberrations limit the attainable null depth to 1-S, where S is the beam Strehl ratio). To mimic the effect of two telescope aperturtes, the input aperture is subdivided, as described later. Finally, although lasers are in general narrowband sources, diode lasers do show finite linewidths of several nm (≈ 0.5%), which immediately brings dispersion issues into play as well. Thus, all aspects of the basic nulling scenario, including all of the problems which need to be addressed, can be tested with a fairly simple laboratory setup.

The actual nulling optics are then as follows: the collimated input beam first strikes a roughly 50/50 (polarization-averaged) dielectric beamsplitter at 45°, and goes on to two 45° flats and the two rooftop mirrors, before returning to the beamsplitter by means of another reflection at the flats (Fig. 1). One of the flats is mounted on a high-precision translation change, which allows for modifications in the OPD between the two nuller arms. The dispersion introduced by passage through the dielectric medium of the beamsplitter plate is corrected to first order via inclusion of a dielectric compensator plate in one of the interferometer's arms.

As a result of residual tilt errors in the rooftop mirrors available (Fig. 2), wavefront quality over the full 25 mm beam aperture was inadequate for deep nulls. However, by limiting the ``output" beam to only one of the quadrants defined by the virtual intersection of the rooftop apex lines, adequate beam quality (λ/5) could nevertheless be obtained. Thus, a 5 mm output aperture was centered in one of the quadrants of the 25 mm output beam to avoid the discontinuities introduced by the rooftop joints. However, introduction of such an output subaperture also serves a more fundamental role: the output aperture defines a geometry completely analogous to that expected in a true nulling beam combiner of this type, with two separate input beams sheared onto each other by the action of the rooftop mirrors. In our case, the output aperture maps back to two distinct (diagonally separated) input sub-beams within the overall input aperture (e.g. Fig. 1a), thus making our tabletop setup an exact analog to the case in which two telescope apertures extract two subsections of the plane wave from a distant star. After the output aperture, the collimated output beam can be passed through a polarizer if desired, and a second achromatic doublet then focuses the output beam onto a single-mode fiber, which transports the light to a fiber-coupled detector. The power meter employed spans 9 orders of magnitude in sensitivity, from 1 mW to 1 pW, providing more than adequate dynamic range.

At this stage, our experiment is not yet set up to achieve active stabilization at the null position. Our initial goal was thus simply the demonstration of a transient null of 10^{-4} for monochromatic, single-polarization visible light, in order to verify the overall optical scheme. For an optically perfect nuller, the power transmission near zero OPD is determined largely by vibration, temperature, and air-current induced fluctuations in OPD. To minimize these environmental limitations on an open-air, vibration-isolated, laboratory tabletop, we took three steps. First, to render low frequency vibrations common mode, the optics were made as compact as possible. Second, to eliminate air currents and acoustic coupling, the nuller was enclosed in a foam box. Finally, the optical mounts were selected for maximum stiffness. Even so, a stable null at the 1 nm level remains beyond the scope of the current simple (feedback-free) setup, and so our goal was the measurement of a transient deep null during an OPD sweep through the null position.

After numerous cycles of component and environmental improvements during 1998, null depths in the range 10^{-4} to 5×10^{-5} were observed during OPD sweeps through the expected null position in Dec. 1998, culminating in an observed nulling ratio of 1 part in 25,000 in Jan. 1999 (Fig. 3). To achieve the deepest null levels, the input laser beam was s-plane polarized on the beamsplitter, the compensator was rotated accurately to correct for the slightly differing beamsplitter and compensator thicknesses, and the output polarizer was inserted into the beam. However, nulls as deep as 1 part in 5000 have also been seen without an output polarizer. The optical principles for achieving a deep null with a rotational shearing interferometer have thus been successfully validated even beyond the requisite level, at least for narrowband radiation.

As to more broadband radiation, a null depth of nearly 10^{-3} has been observed with our nuller for single-polarization, thermal (red) radiation of about 5% bandwidth, but only in a narrow pencil beam. The area of broadband thermal radiation nulling thus remains largely unexplored, as the bandwidth, beam area, and polarization states all need to be broadened to more useful levels. However, fairly straightforward improvements in controlling dispersion are expected to enable substantial progress in this regard. The stabilization of a nulling interferometer at the null position for an extended period of time is also a challenge, but as a nanometer-level control scheme has now been devised for dual-output rotational shearing interferometers[12], there is little reason to believe that this goal cannot also be met in the near term. Thus the fundamental aspects of the enabling technologies for planet searches in the thermal infrared may well be on very firm footing before the millenium is out.

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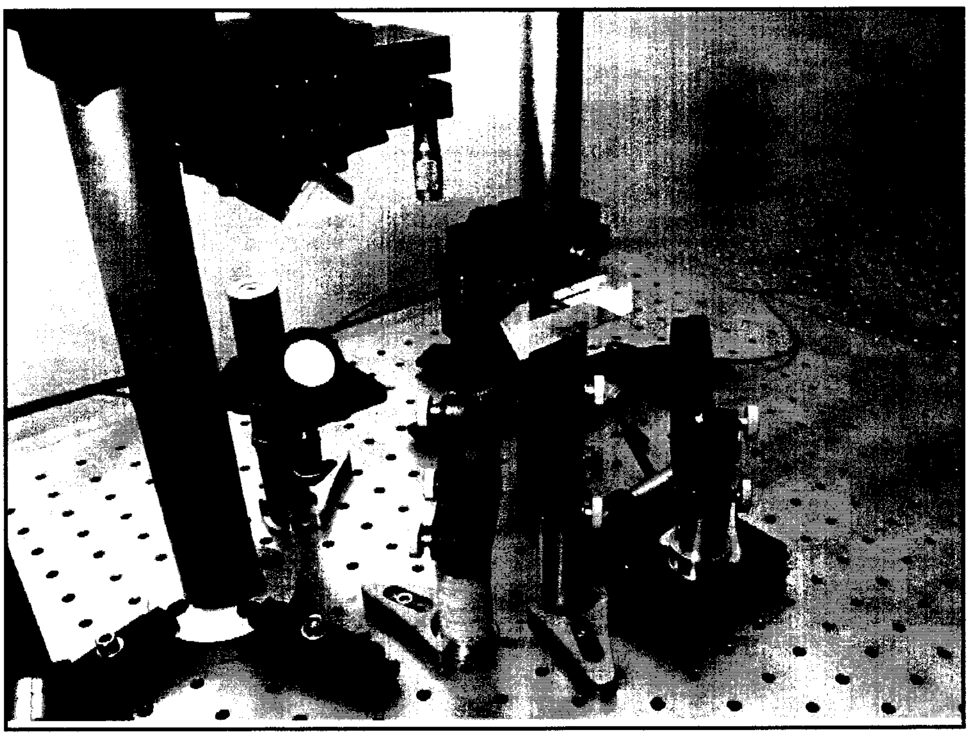
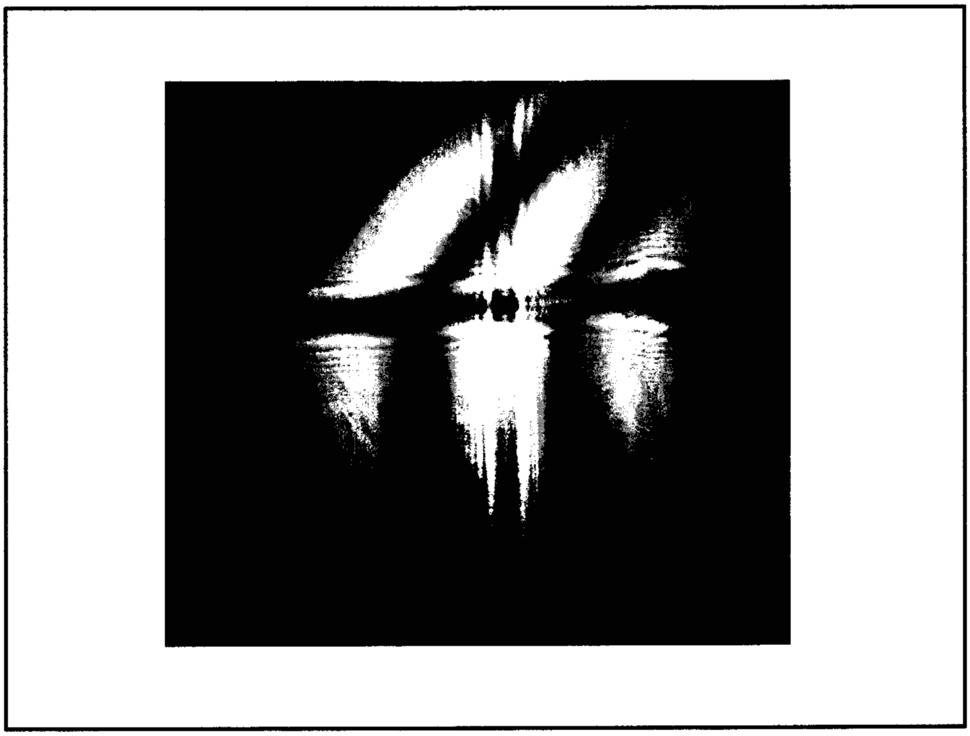
Fig. 1a. Schematic layout of our laboratory nulling interferometer with components labeled. Rooftops A & B are hollow Ag-coated rooftop mirrors, MA & MB are flat mirrors, BS is the beamsplitter, and COMP is the compensator. In our experiment, only one of the two outputs shown is used. The rays reaching this output can be traced, via the two rooftop mirrors, to both of the input beams.

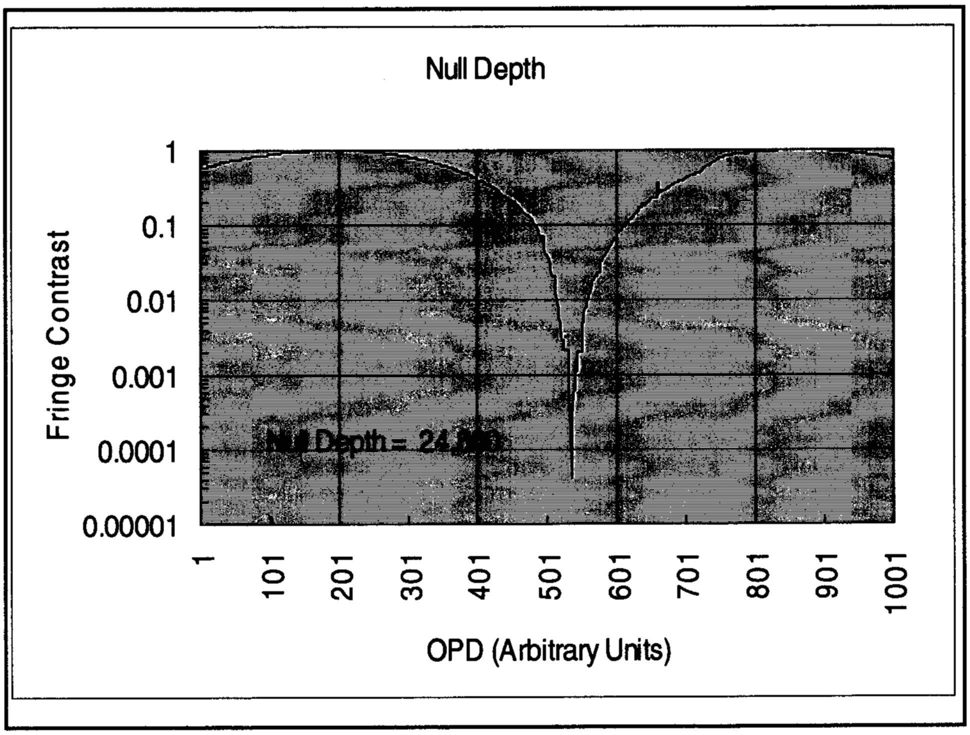
Fig. 1b. Photograph of our laboratory nuller. The beamsplitter, compensator, 2 flats, and 2 rooftops of Fig. 1a can be seen. The maximum dimension is roughly 1 foot. The beam from the laser (not shown) is injected via a single-mode, angle-cut F/5 fiber, which can be twisted to adjust the input polarization state. The intensities of the two combining beams were balanced to a few percent (a prerequisite for nulls of order 10^{-4}) by altering the pointing of the input fiber tip relative to the fixed optical train.

Fig. 2. White light fringes in aperture plane, showing the central dark (blue) fringe, and color symmetry about it. Four fringes of tilt have been introduced across the 1 inch aperture by a misalignment between the two rooftops. The orthogonal shadows of the orthogonal rooftop joint-lines are evident, and the directional change of the fringes across the horizontal joint-line are the result of a residual tilt error between the two halves of one of the rooftop mirrors. The central fringe has a dark blue, rather than black, color, because the input fiber goes multi-mode in the blue. Blue fringes should thus be equated with black. The flipped red and green colors on the two fringes to either side side of the central blue fringe then reflect symmetry about a central dark fringe.

Fig. 3. Intensity recorded by a power detector at the output of the nuller's single mode output fiber, as a function of the optical path difference between the beams in the two arms of the nuller. The input end of the fiber is centered on the nuller's output focal plane pattern, and subtends only the central part of the main diffraction spike. The plot shows a continuous OPD scan of mirror A through the null, where a minimum nulling ratio of 1:24,800 can be seen. The scan rate was roughly 0.1 microns/sec.



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OPD (Arbitrary Units)